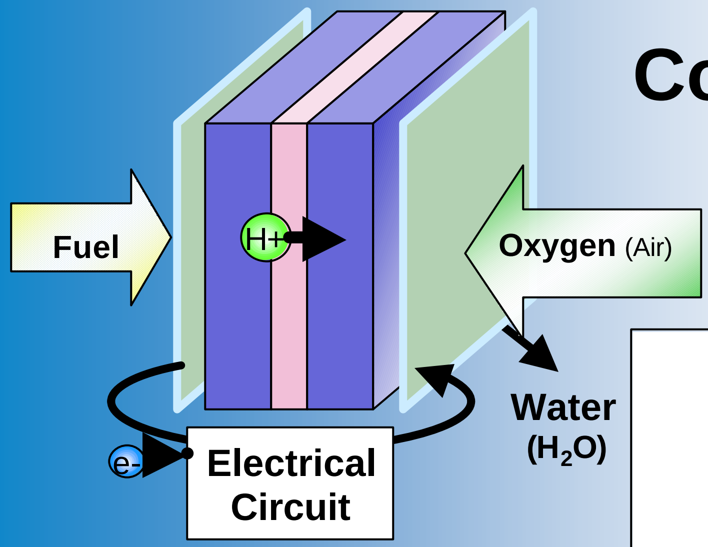
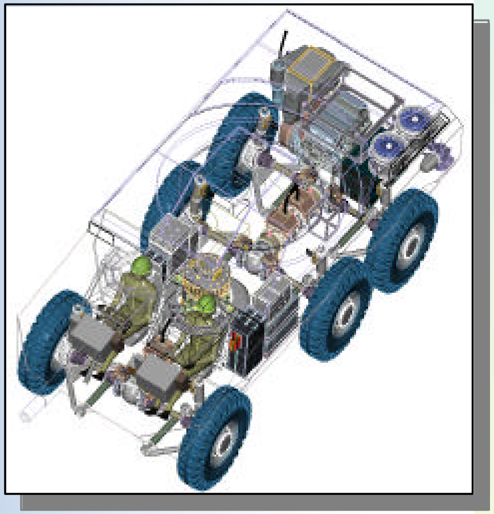
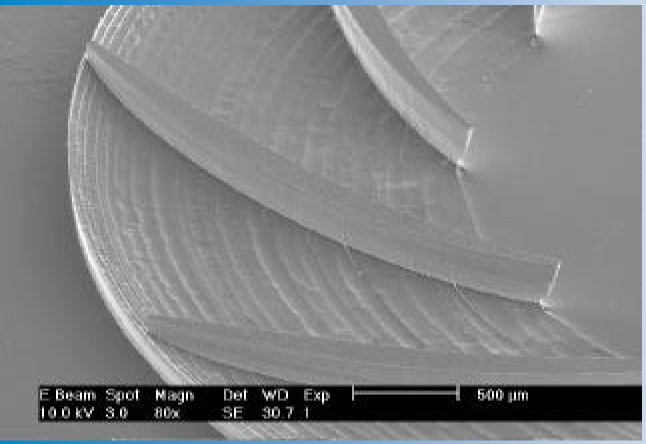
Power & Energy
Collaborative Technology Alliance
(P&E CTA)







Overview

April 29 2003

Mr. John Hopkins
ARL Collaborative Alliance Manager

Dr. Mukund Acharya
Consortium Manager,
Honeywell Engines, Systems & Services

Power and Energy
Collaborative Technology Alliance

Consortium Partners

- Honeywell
- MIT
- Clark Atlanta
- Georgia Tech
- U of Maryland
- Motorola Labs
- NuVant Systems
- Case Western Res U
- Penn State Univ
- Tufts Univ
- U of Minnesota
- U of New Mexico
- U of Pennsylvania
- U of Puerto Rico
- U of Texas – Austin
- SAIC
- Rockwell Scientific
- United Defense LP
- Prairie View A&M
- Rensselear Polytechnic
- Texas A&M

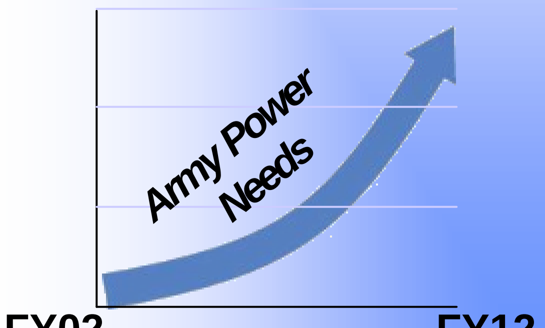
Objectives

Research and develop technologies that enable lightweight, compact power sources and highly power dense components that will significantly reduce the logistics burden, while increasing the survivability and lethality of the soldiers and systems of the highly mobile mounted and dismounted forces of the Army's Objective Force.

Supporting Transformation Goals

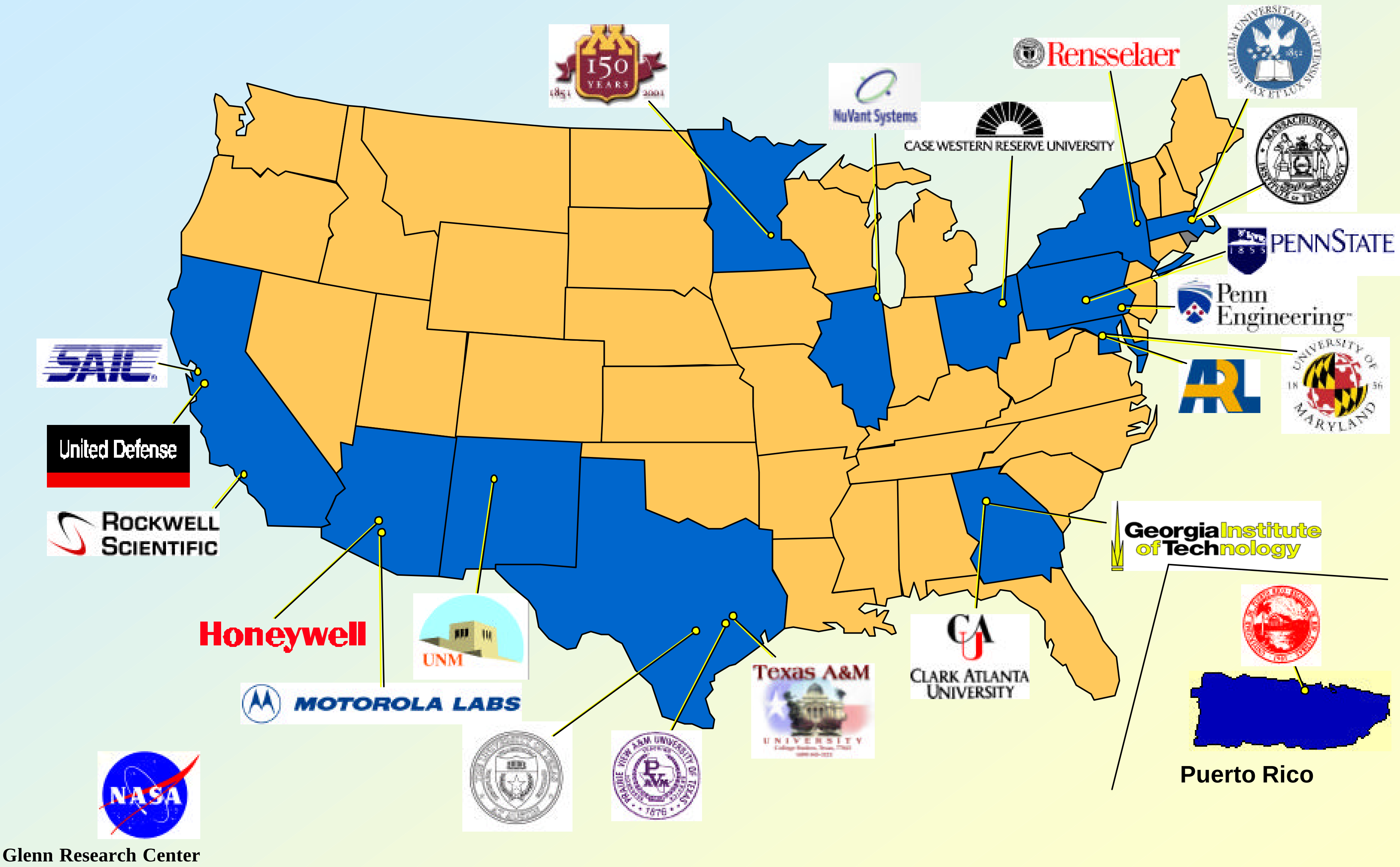
Technical Areas

- Portable, Compact Power Sources (Non-electrochemical)
- Fuel Cells and Fuel Reformation
- Hybrid Electric Propulsion and Power

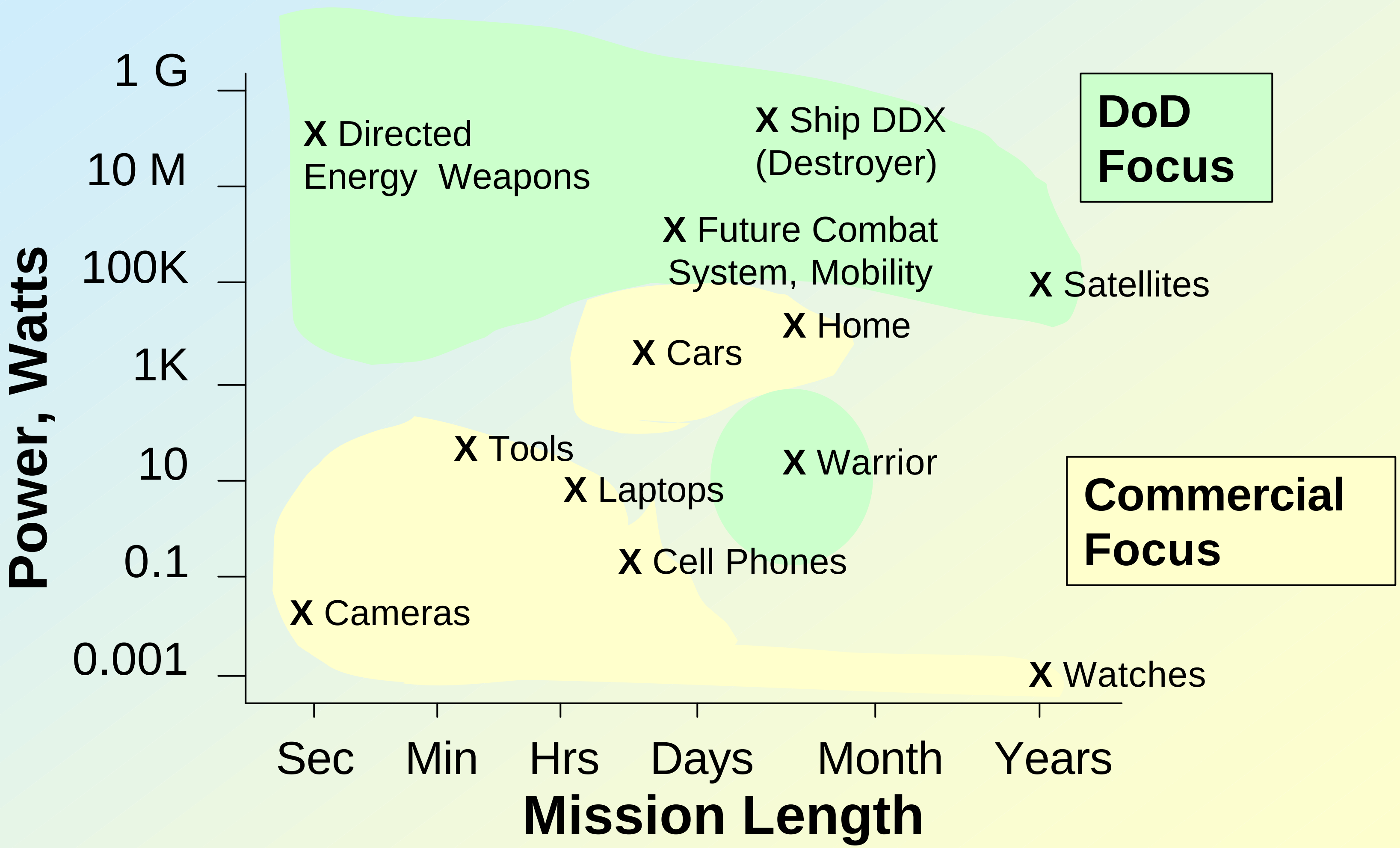


Power and Energy

Collaborative Technology Alliance



DoD and Commercial Industry Requirements



Power and Energy Taxonomy

Operational Regimes

Unit of Action

Responsive Deployable
Agile and Versatile
Lethal Survivable
Sustainable

System of Systems Platforms

- Ground: Manned & Unmanned, Mobile & Non-Mobile
- Air: Manned & Unmanned Aircraft
- Soldier: OFW, Land Warrior
- Unattended Ground Sensors & Munitions

Platform Applications

Hybrid Electric/ Propulsion	Environment Management	Dynamic Armor	EM, ETC, DE Weapons	Active Protection	C4 ISR	Signature Management	UGS, Munitions, Other

Technologies

Switches : Capacitors : Batteries : Power Converters : Fuel Cells : Fuel Reformation Thermal Management : Power Control: Power Generation

Warrior Power

Hybrid JP-8 fueled charger/rechargeable battery system capable of:

- eliminating non-rechargeable batteries
- weighing 1/3 less than non-rechargeables
- extending mission time per system up to 6X

Rechargeable batteries charged 2-3X faster

Power Management design tools reduce power consumption 2 to 5 times.

Required Technology:

- Energy Storage: Battery reactants with 6X increase in energy storage and 3X increase in power density
- Power Control: Efficient chargers for two hour charge time and techniques to reduce power consumption by 50% in Soldier Systems
- Power Generation: Logistic fuel reformation

Payoff in FY08
(1 Battalion, 96 Hour Mission):

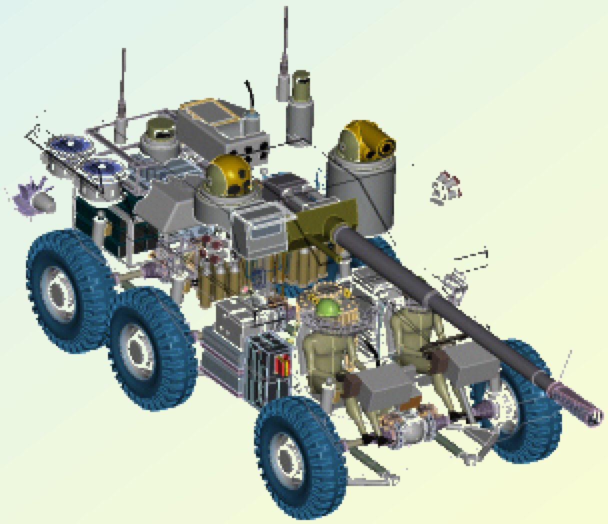
4400 Disposable Batteries, $500,000, 8800 pounds

VERSUS

200 Gallons JP-8, Rechargeable Batteries, $400, 1600 pounds for fuel

Hybrid-Electric Combat Vehicle

- Common power source for propulsion, EM/ETC gun, armor, and auxiliary - ability to shift power away from propulsion
- Enables improved stealth, near silent watch, and extended vehicle range
- > 50% increase in transient power at wheels- enhances mobility
- Increased flexibility of vehicle system integration yields up to 10% increase in useable internal volume

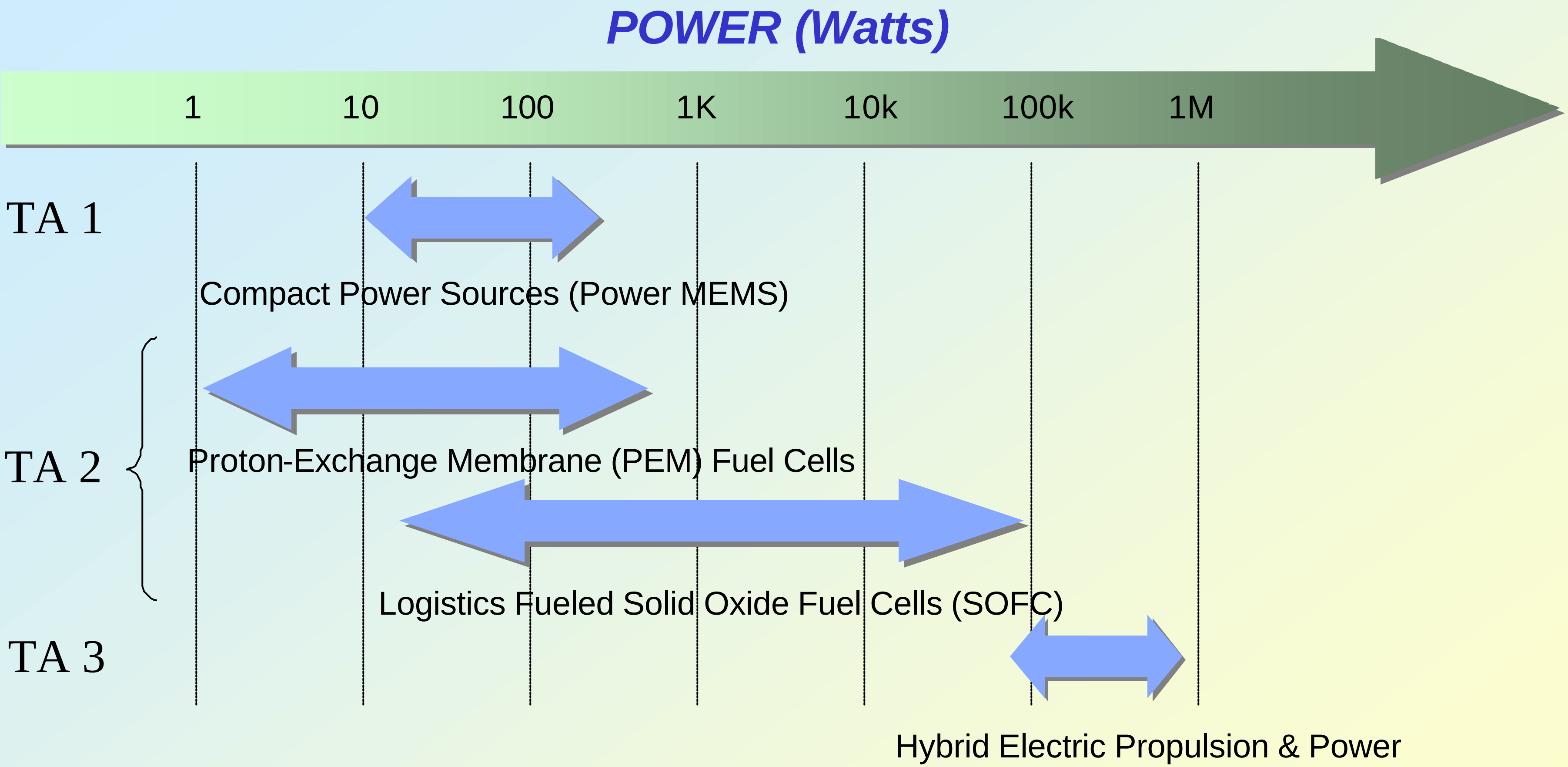


- Required Technology
  - Power Generation: 2X more efficient and 2X more power dense generation
  - Energy Storage: Energy storage at 50 kW-hr (10's MJ) and pulsed power capacitors up to 5 MW
  - Power Control and Distribution: High power switches, control and distribution

Payoff in FY2010:

- Fuel savings up to 50%
- Reduction in armor and ammunition weight hence transport costs
- New capability for EM/ETC gun and dynamic armor

P&E CTA Focused on Three Technical Areas



Technical Area Power Levels Meet the Goals of Transformation for Soldier and Vehicular Loads

Power and Energy Collaborative Technology Alliance

PM: Honeywell ES&S, Dr. Mukund Acharya
CAM: ARL, John Hopkins

Portable Compact Power Sources

MIT, Dr. Alan Epstein
ARL, Eugene Zakar

- MEMS Magnetic Generators
- Microfabrication Technology
- MEMS Gas Turbine Generators

Fuel Cells & Fuel Reformation

Motorola, Jerry Hallmark
U. Penn, Dr. John Vohs
ARL, Dr. Deryn Chu

- DMFC Catalysts
- Polymeric Membranes
- DMFC Design, Model, Prototype
- RHFC Catalysts and Support
- High-temp MEA
- RHFC System

- Low-temp SOFC Materials
- Direct Hydrocarbon reforming anode
- SOFC Cell Fab, Eval, Testing
- Logistics Fuel Reformation Catalysts
- Hi-temp Fuel Desulfurization
- Logistics Fuel Reformation CPOX & Desulfurization

Hybrid Electric Propulsion & Power

SAIC, George Frazier
Honeywell, Jochen Deman
ARL, Dr. Ken Jones

- Hi-speed Ceramic Turbogenerator
- Turbo-electric compounded diesel
- Matrix Converter
- DC/DC Converter
- SiC Materials/Devices
- Electric Machines
- Systems Analysis

ARL In-House Program

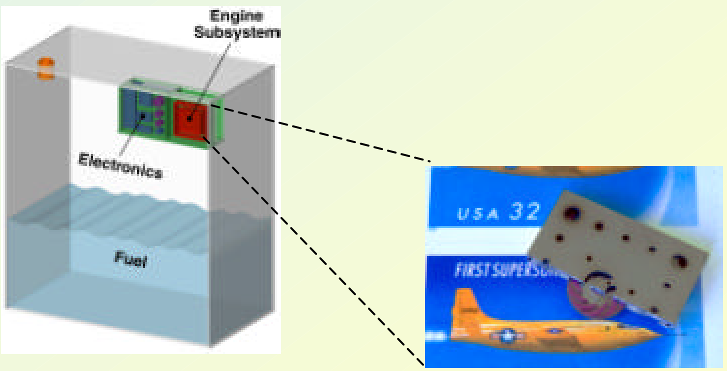
ARL In-House Expertise

P&E TA 1: Portable, Compact Power Sources
(Non-electrochemical)

Objective: Develop/demonstrate MEMS gas turbine generator for revolutionary non-electrochemical soldier power sources, having 10X greater energy density than current batteries and capable of meeting the power and energy requirements of the Objective Force Warrior.

Approach

- Simple cycle gas turbine
- Direct drive generator (1.2M RPM)
- MEMS fabrication



Near-term performance goals

- 5% efficiency (chemical to electrical)
- 10 watts output

Challenges:

- Achievement of acceptable energy conversion efficiency
- Precision microfabrication and alignment
- Microfabrication of high temperature materials
- Incorporation of battlefield robustness and low signature emission

Portable Compact Power Sources
– Research Team –

MIT → Gas Turbine & Electrostatic Generator

Electromagnetic Generator ← Georgia Tech, Clark Atlanta

U. of Maryland → Micro fabrication Technology

Component Fabrication & Process Development ← Army Research Laboratory

TA-1 FY02 Accomplishments

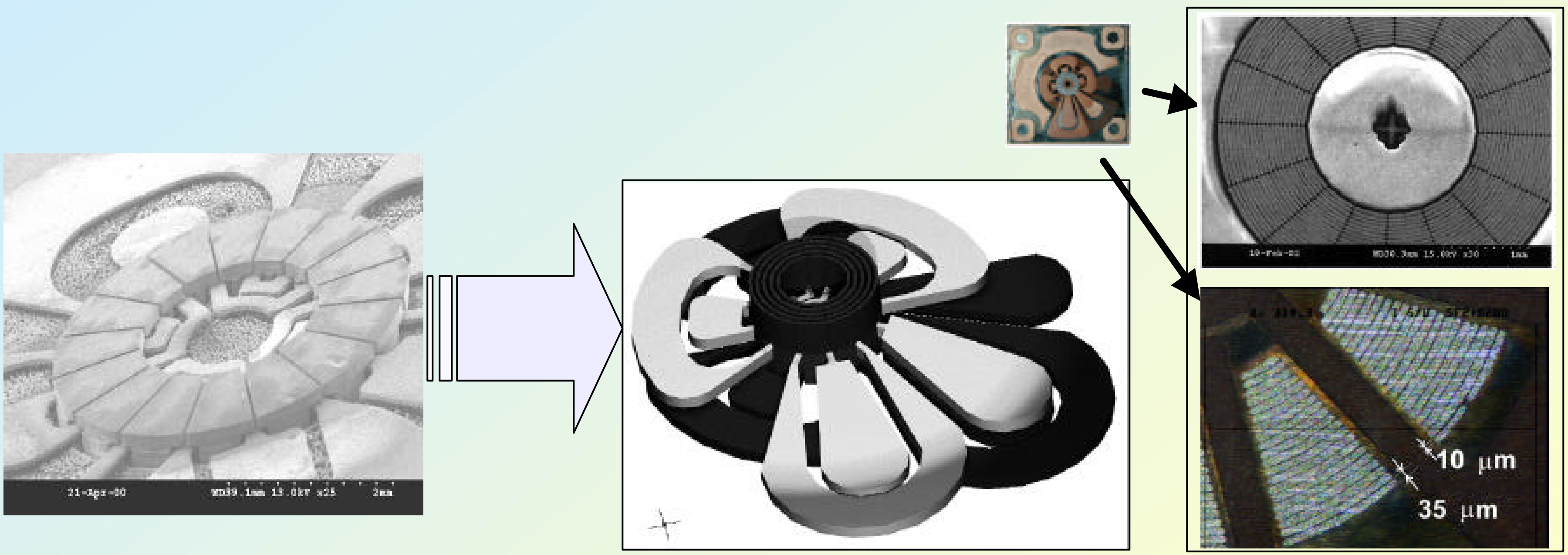
- Micro gas turbine engine/turbocharger
  - High speed (380,000 rpm) turbomachinery testing (MIT)
  - Catalytic propane microcombustor tested (MIT)
- Electrostatic generator
  - 1st air turbine generator tested (MIT)
  - Low speed (50,000 rpm) confirms theory (MIT)
- Magnetic generator
  - Proof-of-principle tethered motor tests confirm theory (GIT, MIT)
  - Improved performance laminated microstator structure built (GIT, CAU)
- New micromachining processes
  - Continuously variable height silicon structure demonstrated (UMD)

TA-1 Goals For FY03

- 1QFY
  - Ignition in 1st generation (V1) H_2 MicroEngine (MIT)
- 2QFY
  - 1st generation H_2 MicroEngine operated at high power (MIT)
- 3QFY
  - V1 Electrostatic generator tested to maximum power (MIT)
- 4QFY
  - CDR of magnetic motor/generator V1 (GIT, CAU, MIT)
  - PDR of 2nd generation engine (MIT)
  - Delivery of 1st in-spec, variable height compressor wafer to MIT (UMD)

Portable Compact Power Sources
LAMINATED MAGNETIC GENERATOR STATOR

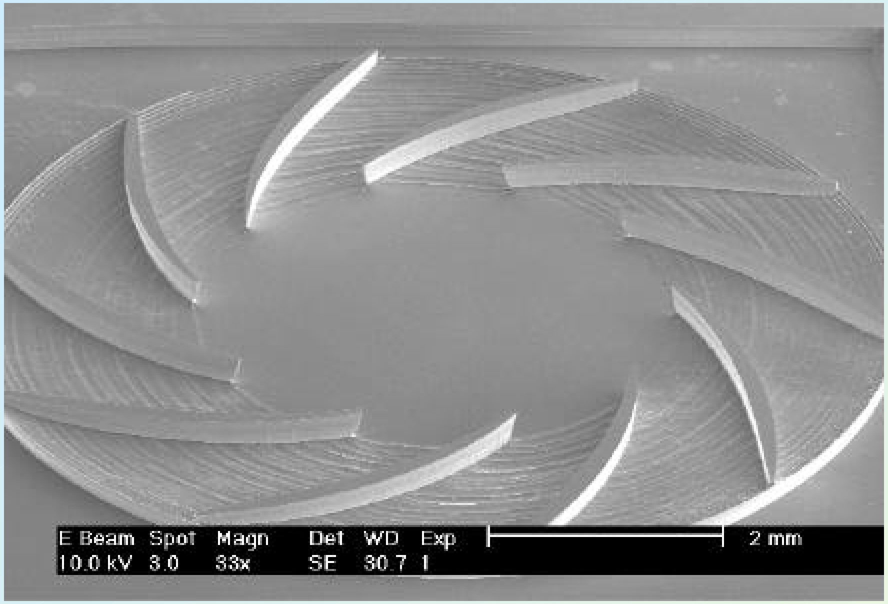
Non laminated magnetic structure → **Laminated magnetic structure**

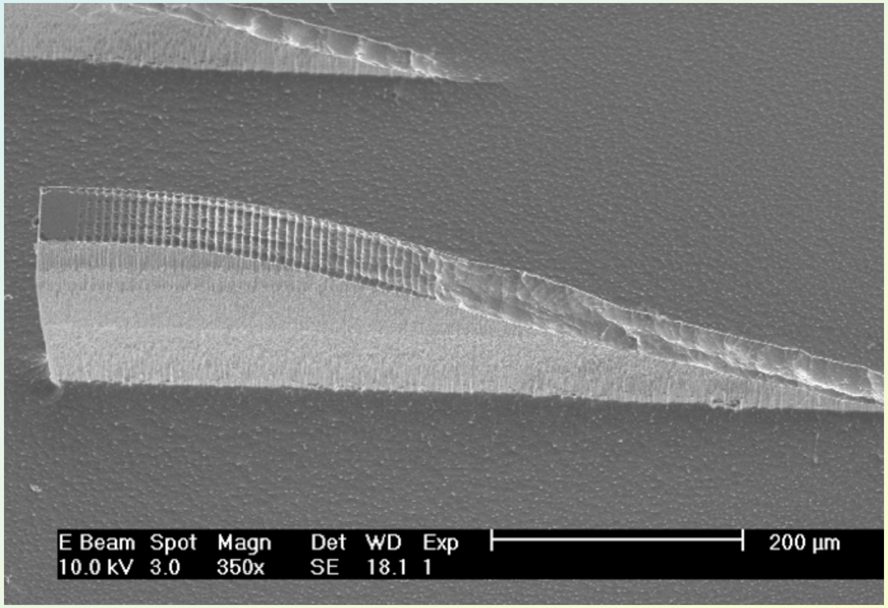


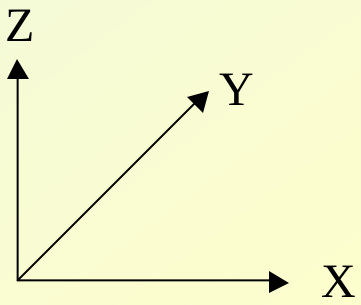
- **Laminations reduce eddy current losses**
- **Laminated microstructures were beyond the SOA**
- **New fab processes developed & demonstrated**

3-D Profiles in Photoresist Film

-FY02 UMD Accomplishment-

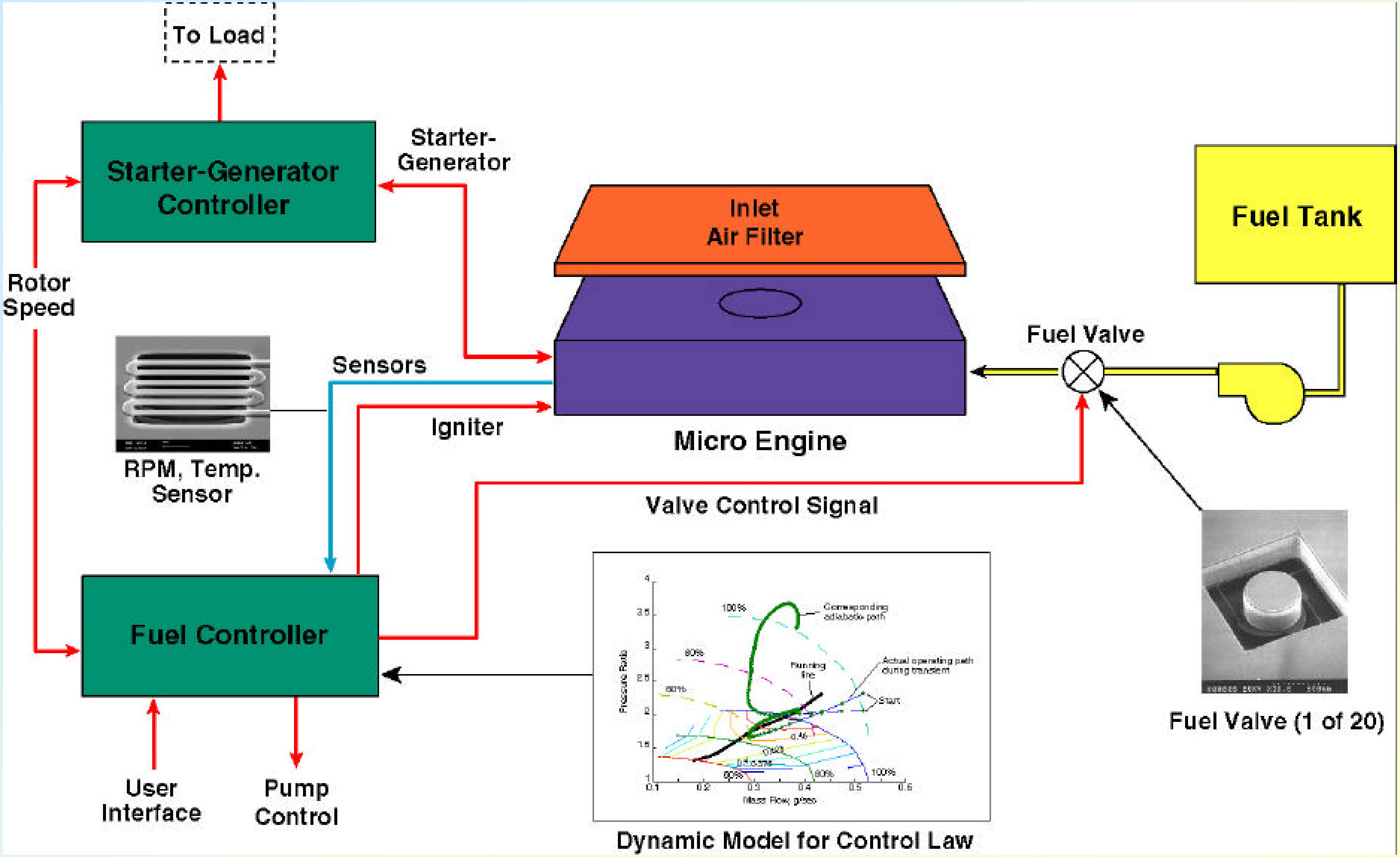






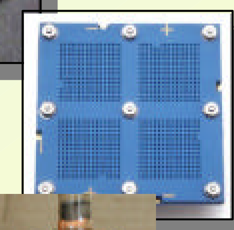
- Historically Si etching is 2-D, i.e. prismatic
- Gas turbine use extensive 3-D geometries
- Micro engine design is currently compromised to stay 2-D
- Grey-scale lithography makes 3-D structures possible

ENGINE AUXILIARY SYSTEMS NEEDED



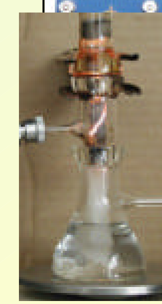
P&E TA 2: Fuel Cells and Fuel Reformation

Objective: Provide enabling technologies for soldier portable fuel cell systems, including fuel processing for hydrogen generation and storage. Provide enabling technologies for logistics fuel reformation and fuel cells for vehicle propulsion.



Challenges:

- Battlefield robustness, including load following and temperature extremes
- Rate controlling catalytic chemical processes
- H_2 storage and/or microreforming of fuel
- Improved electrocatalysts, electrolytes for DMFC
- Range and variation in logistics fuel constituents: high sulfur content, etc.



Research Tasks:

- DMFC Catalysts
- Polymeric Membranes
- DMFC design, model, prototype
- RHFC Catalyst and Support
- High-Temp MEA
- RHFC System
- Low-temp SOFC Materials
- Direct Hydrocarbon Reforming Anode
- SOFC Cell Fab, Evaluation, Testing
- Logistics Fuel Reformation Catalysts
- High-temp Fuel Desulfurization
- Logistics Fuel Reformation: CPOX and Desulfurization

Fuel Cells and Fuel Reformation
PEM Fuel Cells
–Research Team –

Motorola Labs → DMFC Membranes
DMFC/RHFC systems,
peripherals, integration

DMFC Catalysts ← Penn State, U. Puerto Rico
NuVant Systems

U. of New Mexico → Methanol Reforming
Catalysts

High Temperature (180C)
Membrane Electrode Assembly ← Case Western Reserve U.

Army Research
Laboratory → DMFC Catalysts,
Low Methanol Crossover Membranes (80C),
High Temperature Membranes (180C)

Fuel Cells and Fuel Reformation
PEMFCs – DMFC & RHFC
Accomplishments for FY 02

DMFC Catalysts

- Catalyst screening methodology and system in place
- Computational study for transition state for reactions on catalyst surface

DMFC System (Motorola)

- Initial system design and modeling of 1W planar DMFC system
- Fabrication of 1W CMEMS DMFC substrate

MSR Catalyst Support (UNM)

- Successfully wall coated quartz tubes of 3mm ID and shown that the reactivity of this catalyst is better than the packed bed catalyst

HT PBI MEA (CWRU)

- Microband apparatus designed, built, tested for O_2 reduction.

RHFC System (Motorola)

- Initial Design and characterization of 2.5W fuel processor.

Fuel Cells and Fuel Reformation

PEMFCs – DMFC & RHFC

Goals for FY 03

DMFC Catalysts

- Prepare and characterize Pt-Ru-Ir ternary compositions by Reetz method & investigate stronger reducing agents for extending Reetz methods to Os and Mo (PSU)
- Identify transition states for water dissociation, CO(ads) and OH(ads) on Pt/Ru using quantum mechanical methods (UPR)

DMFC System (Motorola)

- Prepare morphological family of block copolymers targeting good film properties & evaluate potential of this family in DMFC applications.
- Fabricate 1-2W Prototype Operating 1 week at > 200Wh/L

MSR Catalyst Support (UNM)

- Reactivity tests on wall coated catalyst formulations

HT PBI MEA (CWRU)

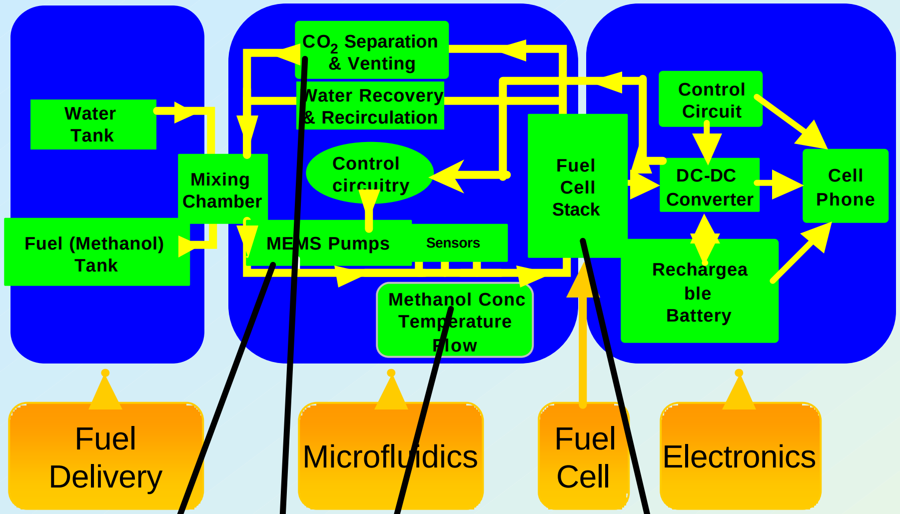
- Complete characterization of O2 kinetics on Pt alloy catalysts using microband cell

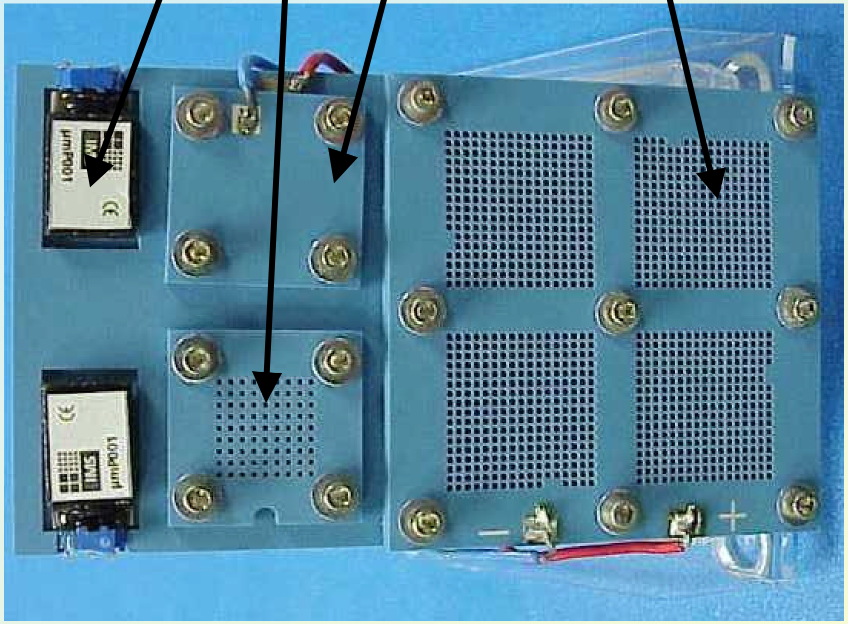
RHFC System (Motorola)

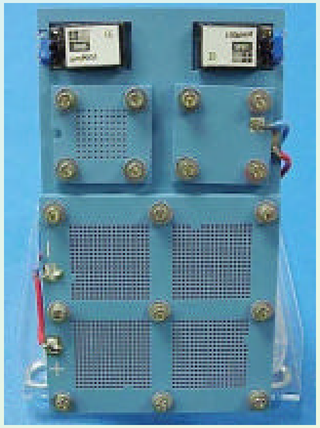
- Demonstrate 2-5W RHFC system
- Incorporate new materials generated from CTA work

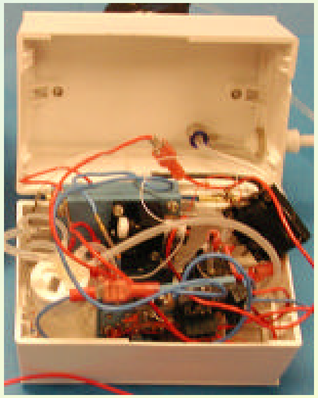
PEM Fuel Cells

DMFC System: Motorola









1W DMFC Prototype

Fuel Cells and Fuel Reformation
SOFC and Logistics Fuel Reformation
– Research Team –

U. Texas at Austin → Low-Temperature SOFC Materials: Cathode and Electrolyte

Direct Oxidation Anodes ← U. Pennsylvania

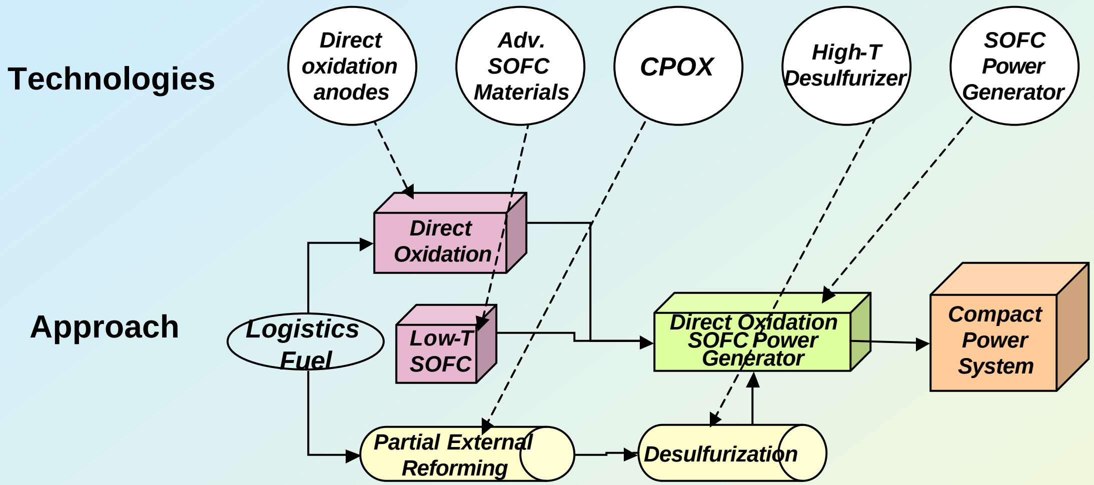
Tufts University → High-Temperature Fuel Desulfurization

Catalytic Partial Oxidation for Logistics Fuel Reformation ← U. Minnesota

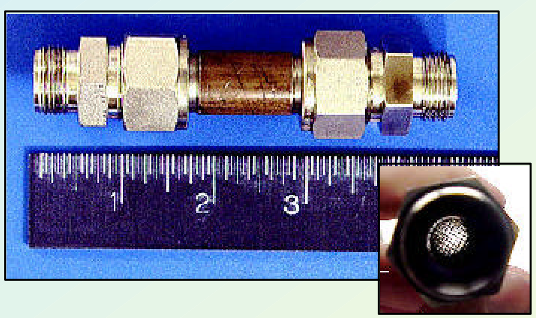
Army Research Laboratory → Water Gas Shift Catalysts for CO Cleanup

Fuel Cells and Fuel Reformation

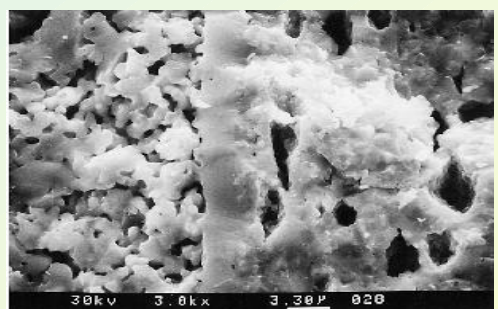
SOFC and Logistics Fuel Reformation



The solid oxide fuel cell (SOFC) runs directly on hydrocarbons or logistics fuel or on hydrogen and CO generated from a fuel reformer, such as a catalytic partial oxidation reactor (CPOX)



Catalytic Partial Oxidation Reactor (CPOX) for 1 kW SOFC stack



$LaMnO_3$ Cathode | ZrO_2 Electrolyte | NiO/ZrO_2 Anode

Cross section of SOFC cell

SOFC stack

SOFC Logistics Fuel Reformation & Direct Oxidation

Accomplishments for FY '02

- LaGaO3-based electrolytes shown to be stable against logistic fuels
- Developed Cu-CeO_2-SDC direct oxidation anodes for cells with SDC electrolyte.
- Developed Cu-CeO_2-Sc-doped zirconia (SDZ) direct oxidation anodes for cells with SDC electrolyte.
- Demonstrated stable performance while operating directly with butane fuel for both SDC and SDZ cells
- JP-8 and Diesel successfully reformed
- Evaluated different sorbent compositions at various operating conditions
- Showed that La_2O_3 is the preferred dopant in Cu-CeO_2, while ZrO_2 has a negligible effect on its sulfur capacity.

SOFC Logistics Fuel Reformation & Direct Oxidation

-Goals for FY '03-

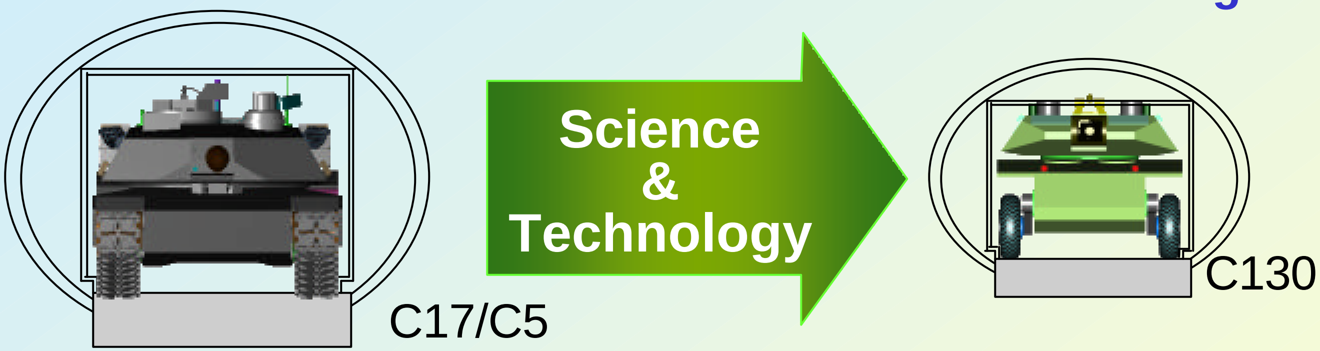
- Continue development of low-temperature cathodes and direct oxidation anodes
  - Complete characterization of catalytic properties of anodes and cathodes
  - Test anode performance with higher hydrocarbon fuels (e.g. decane and toluene) that simulate the properties of JP-8
- Begin integrating cathode and anode improvements into a single fuel cell design
  - Construct and test cells that use Cu/ceria direct oxidation anodes developed at U. Penn with high performance, $SrCo_{0.8}Fe_{0.2}O_{3-d}$ cathodes developed at U. Texas
- Desulfurization of high-temperature reformate gas
  - Complete characterization of Cu-ceria-based sorbents
  - Begin integration of CPOX and desulfurization systems
- Begin integrating CPOX and SOFC systems
  - Test SOFC performance while running on partially reformed fuel produced by a CPOX reactor
  - Determine to what degree heavy hydrocarbon fuels will need to be reformed in order to avoid tar formation

P&E TA 3: Hybrid Electric Propulsion and Power

Objective: **Provide enabling technologies supporting efficient, compact, light-weight energy conversion and electric power conversion and conditioning for FCS and robotic platforms.**

Objective Force Driver:

Reduce Combat Vehicle Size and Weight

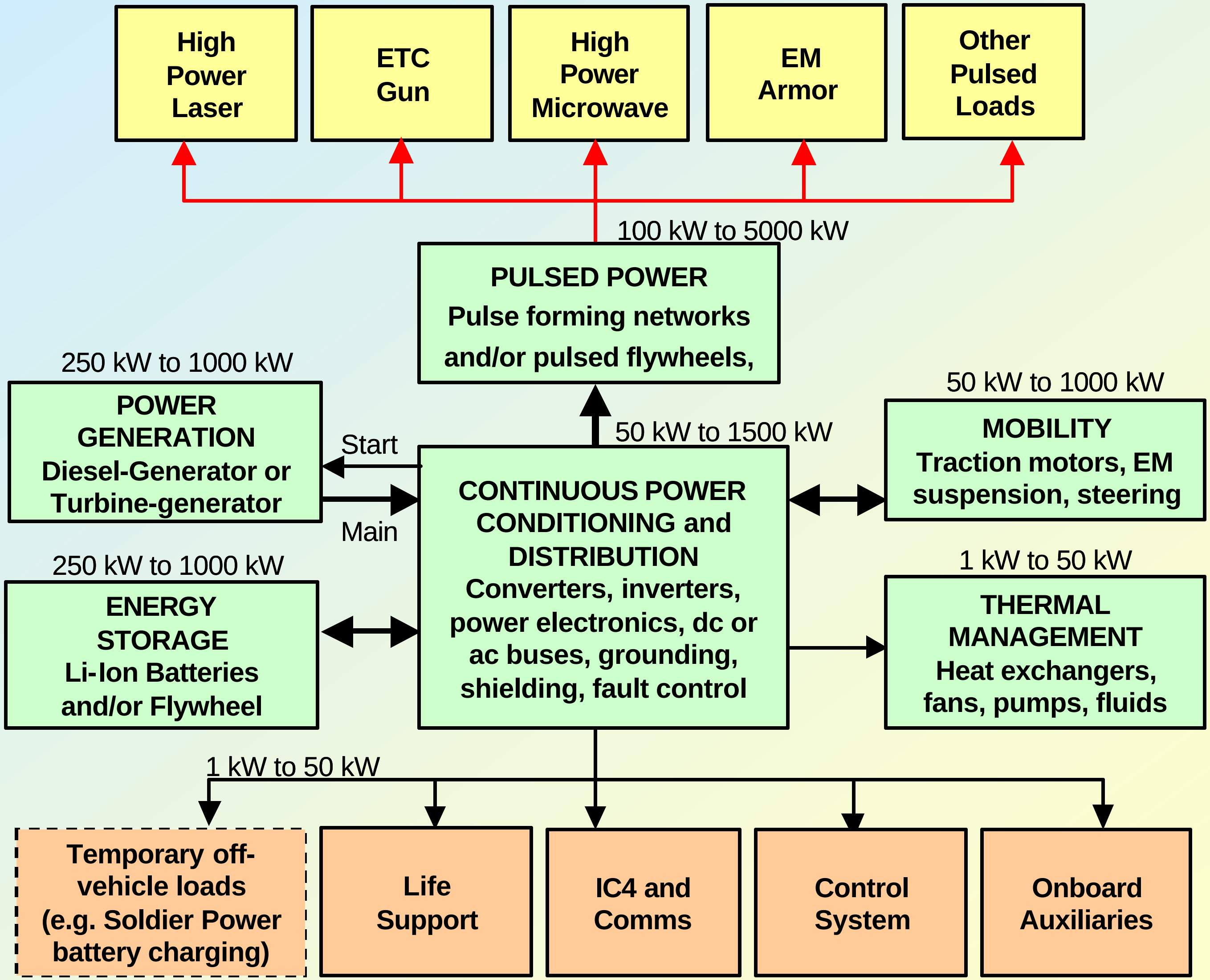


Up to:
70% Lighter
50% Smaller

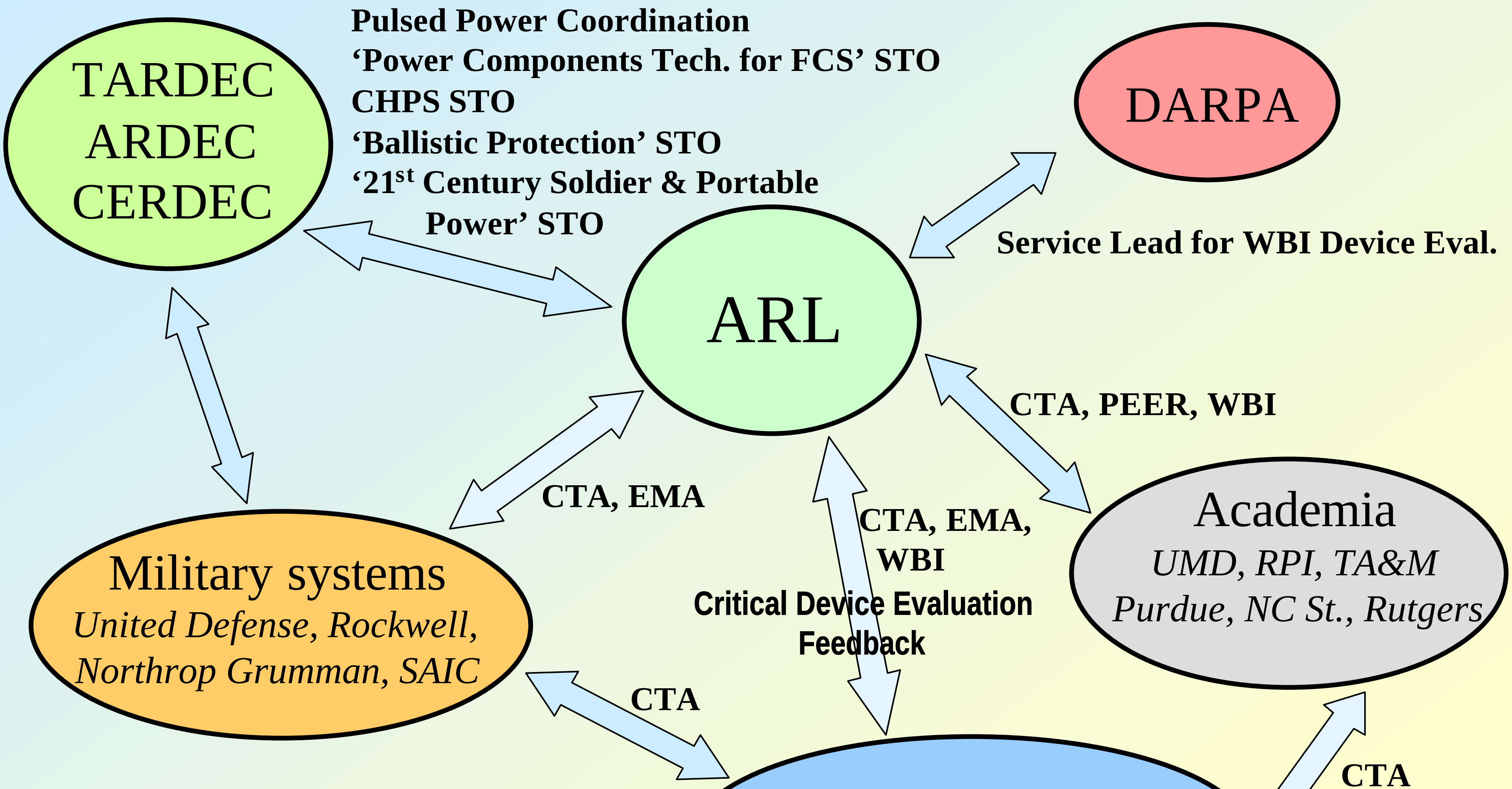
Current System	Future Combat System Platforms
60-70 Tons	18 +/- Tons
650 Cu. Ft. Internal Volume	300-400 Cu. Ft. Internal Volume

Multi-pronged Approach: **Develop high-power-density engine and generator technologies, improve fabrication techniques and thermal management for silicon-carbide devices, and power- conversion systems for pulsed and mobility power, system design and modeling.**

Basic Combat Hybrid Power System Architecture



SiC Device & Component Development and Integration Coordination



CTA = Collaborative Technology Alliance
EMA = Electro-Magnetic Armor program
PEER = Power and Energy Electronics Research
WBI = Wide Bandgap Initiative

Hybrid Electric Propulsion & Power
– Research Team –

SAIC	→	System Design and Modeling Device Integration & Analysis
High Temperature Ceramic Turbogenerator	←	Honeywell
United Defense	→	DC-DC Converter Turbocompound Diesel
SiC Devices	←	RPI, Cree
Army Research Laboratory	→	SiC Device Fabrication, Evaluation & Process Improvements, Converter Design
Matrix Converter	←	Rockwell
Texas A&M, Prairie View	→	Electric Machines & Drives

Hybrid Electric Propulsion and Power
FY 03 Annual Program Plan Milestones

Hybrid Electric Propulsion & Power

SAIC, George Frazier
Honeywell, John Meier
ARL, Dr. Ken Jones

- Hi-Speed Ceramic Turbogenerator
- Turbo-Electric Compounded Diesel
- SiC Devices
- DC/DC Converter
- Matrix Converter
- Electric Machine Drives
- Modeling and Simulation

Modeling and Simulation

- Develop and document continuous power load data base for FCS
- Investigate integrating ARL Power Budget Tool into CHPSet multi-physics hybrid electric codes.

Extended Matrix Converter

- Investigate high frequency capabilities
- Predict theoretical performance ranges based on existing technology

Turbo-Electric Compounded Diesel

- Investigate reasons why computer analyses showed less than expected fuel economy & power density gains

Electric Machine Drives

- Develop and demonstrate sensorless switched reluctance motor drive
- Develop control method for permanent magnet generators

SiC Devices

- 5kV, 10A epi-anode PIN diodes
- 1200V, 1A trench, and 15 A planar JBS rectifiers
- 600V, 15A 4H-SiC epi-emitter BJTs

DC/DC Converter

- Develop and test 1200 V, 600 A hybrid Si/SiC switch assembly
- Develop high power DC-DC converter power density roadmap

High-Speed Ceramic Turbogenerator

- Continue research leading to 300 kW Demonstrator

Summary

- *Army must focus power and energy investment on Transformation challenges and problems and leverage commercial industry, academia, other services and agencies*

- *Increased Army investment (FY04-09) will aid development of key power and energy technologies*

- *Power & Energy CTA is a vital piece to the puzzle providing many collaborative and leveraging opportunities on the road to transitioning technologies into the Future Combat System, Objective Force Warrior and the Objective Force*